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ADAPTIVE INTEGRATION OF HEAD-COUPLED MULTI-SENSORY DISPLAYS FOR TARGET LOCALIZATION

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The purpose of this study was to determine the efficacy of providing target location information via head-coupled visual and spatial audio displays presented in adaptive and non-adaptive configurations. Twelve USAF pilots performed a simulated flight task in which they were instructed to maintain flight parameters while searching for ground and air targets. The integration of visual displays with spatial audio cueing enhanced performance efficiency, especially when targets were most difficult to detect. Several of the interface conditions were also associated with lower ratings of perceived mental workload. The benefits associated with multi-sensory cueing were equivalent in both adaptive and non-adaptive configurations.

INTRODUCTION

An important consideration for implementing displays is their interaction with existing interfaces. Cockpits have limited space for information display, and there is already a high visual demand that may contribute to information overload and increase the probability of pilot error (Reising, Liggett, & Munns, 1999; Weinstein & Wickens 1992). A promising approach to counteracting visual overload is the use of multi-sensory adaptive interfaces, in which automation is employed to control the delivery of information to pilots so that they receive the right information in the right format at the right time, and are not otherwise exposed to that information (Hettinger, Cress, Brickman, & Haas, 1996; Hollnagel, 1988). Along this line, the benefits associated with the adaptive interface approach may be best realized in extreme environments, where task demands often exceed the perceptual and cognitive capabilities of the operator.

For example, tactical air missions place a high visual load on pilots, who must rapidly acquire and synthesize information from displays *inside* the cockpit and events *outside* of the cockpit (Martin-Emerson & Wickens, 1997). While the development of head-up (HUD) and helmet-mounted displays (HMD) has been shown to improve performance in target detection scenarios (Fadden, Ververs, & Wickens, 1998; Osgood, Wells, & Meador, 1995), these technologies have several limitations which may constrain their effectiveness (e.g., narrow FOV, excessive helmet weight, etc.).

One potential solution for offsetting these limitations is the use of spatial audio displays, which have been shown to enhance target detection performance and reduce overall levels of workload during visual search tasks (Bolia, D'Angelo, & McKinley, in press; Nelson, Hettinger, Cunningham, Brickman, Haas, & McKinley, 1998; Perrott, Cisneros, McKinley, & D'Angelo, 1996). Despite these recent empirical findings, similar investigations conducted in operationally-relevant environments, such as tactical aviation, have been sparse (Bronkhorst, Veltman, & van Breda, 1996). The purpose of the present investigation was to evaluate the role of adaptive integration of visual and spatial audio displays for target detection and designation during a simulated low-level terrain avoidance flight task.

METHOD

Participants

Twelve pilots (11 males and 1 female) serving at Wright-Patterson Air Force Base participated in the study. They ranged in age from 32 to 51 years, with a mean of 40 years. All reported normal or corrected-to-normal vision, and normal hearing. Each pilot had at least 1500 hours of flight experience in military aircraft, with a mean of 2652 hours logged.

Experimental Design

Seven *interface conditions* were combined factorially with two *target types* (ground and air) and two *initial target location* conditions (within and beyond ± 15° of the participant's instantaneous head orientation) in a completely within-subjects design. The interface conditions comprised a non-cueing control and six target-cueing interfaces, including spatial auditory, unimodal visual, and multimodal (auditory and visual) displays presented in fixed or adaptive configurations.

Under all but the Non-Cueing condition, visual and/or spatial audio cues were provided to aid in locating targets. In situations in which visual cueing was provided, target location and range were provided by a look-to line display (see Figure 1) projected onto the wide field of view dome display and slaved to the pilot's head position.

Spatial audio cueing consisted of broadband noise pulses (250 ms, 70dBA), digitally-filtered using a Convolvotron Audio Rendering System configured with non-individualized head-related transfer functions, and presented binaurally over Sennheiser HD250 II headphones. Target range was indicated by inter-pulse interval (IPI), such that shorter IPIs indicated closer targets.

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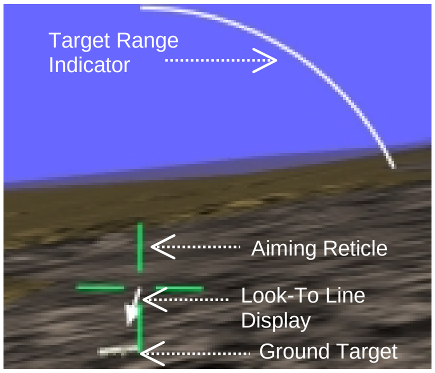

Figure 1. Head-slaved visual display symbology. Target location was indicated by the direction of an arrow, which diminished in length as the angle separation between the pilot's head orientation and target location decreased. Changes in target range were portrayed by changes in the circumference of a circle centered in the pilot's field of view.

In the non-adaptive display conditions (Auditory, Visual, and Auditory+Visual), spatial audio and/or visual cues appeared whenever a target was present in the field of regard. Conversely, in the adaptive display conditions, modality of presentation was determined by the location of the target in relation to the orientation of the pilot's head. For example, in the Adaptive Auditory + Adaptive Visual display condition, the locations of targets more than ±15° from the center of the pilot's head orientation were cued with the spatial audio display. However, as the target moved within ±15° of the pilot's field of view, the spatial audio cue was replaced by the look-to line display. In the Adaptive Auditory + Non-adaptive Visual display condition, the use of spatial audio cueing was once again determined by target locations in excess of ±15° from the center of the pilot's head orientation, while the visual cueing display was always present. In the Adaptive Visual + Non-adaptive Auditory condition, the look-to visual display was only presented when targets were located within ±15° of the center of the pilot's head orientation, while spatial audio cues were provided regardless of target location.

Apparatus and Procedure

SIRE Facility. The study was conducted at the Air Force Research Laboratory's Synthesized Immersion Research Environment (SIRE) at Wright-Patterson Air Force Base, Ohio. The SIRE facility houses a fixed-base cockpit situated in the center of a 6.1 m radius dome that includes a high-resolution, large field-of-view (70° vertical by 150° horizontal) interactive visual display. The cockpit contained head-up and head-down visual displays, throttle and sidestick aircraft controls, a head position and orientation tracker, and a Convolvotron spatial audio rendering system. Out-the-window imagery consisted of desert-like mountainous terrain. All aspects of the experiment were controlled by digital computers.

Flight Task. Pilots were instructed to maintain an airspeed of 500 knots while flying at or below 300´ above ground level (AGL). The flight task also required pilots to minimize lateral deviation from a waypoint-guided flight path, comprising three waypoints, each of which were separated by approximately 31.38 km. Deviations from the flight path were indicated on the Horizontal-Situation-Display (HSD). Additional avionics information, including aircraft heading, airspeed, and AGL altitude were presented on a 30° FOV HUD.

Target Designation Task. While maintaining the directed flight parameters, pilots visually searched the out-the-window scene for ground and air targets, SCUD launchers and MH-53 helicopters, respectively. Eight ground and eight air targets were randomly distributed along the flight path on each experimental trial. Pilots were instructed to visually locate and designate targets as quickly as possible by moving a head-coupled aiming reticle, projected onto the dome, over a target and depressing the appropriate control-stick button. A correct designation (hit) was defined as an appropriate button press while the aiming reticle was within 3° of the target.

Procedure. For each interface condition, pilots completed a block of five consecutive trials. Immediately following the completion of each condition, pilots assessed the perceived mental workload of the task via the NASA-Task Load Index (TLX; Hart & Staveland, 1988). Search performance under the adaptive and non-adaptive interface configurations was assessed in terms of target designation performance, designation time, and patterns of head motion.

RESULTS

Designation Accuracy

Mean percentages of correct detections were calculated for all experimental conditions, converted to arsines (Winer, Brown, & Michels, 1991), and submitted to a 2 (initial target location) × 2 (target type) × 7 (interface condition) repeated measures ANOVA. The results of the analysis revealed significant main effects for *target type*, $F(1,11) = 463.60$, $p < .05$ and *interface condition*, $F(3,40) = 61.64$, $p < .05$, and a significant *target type* × *interface condition* interaction, $F(3,40) = 17.20$, $p < .05$. These effects are illustrated in Figure 2.

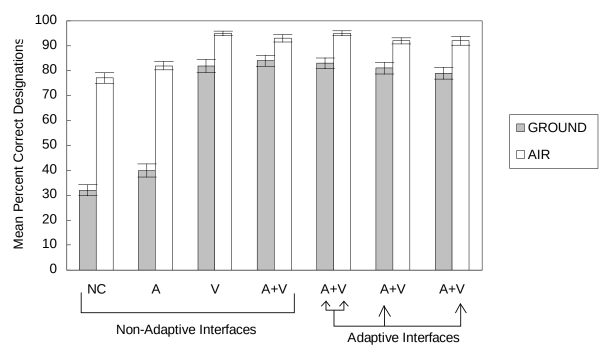

Figure 2. Mean percent correct designations for ground and air targets under all interface conditions (NC = Non-Cueing; A = Auditory; V = Visual; A+V = Auditory+Visual). Designation scores associated with the non-adaptive and adaptive interface conditions appear on the left and right sides of the graph, respectively. The adaptive components of the interfaces are indicated by arrows.

Designation Time

As was seen in Figure 2, detection performance in the

Non-cueing and Auditory conditions was significantly worse than in all other interface conditions. These data were thus excluded from the analysis of designation time – the time required to correctly designate a target – to guard against unreliable estimates of the means due to biases associated with differences in sample size.

Mean designation time scores were submitted to a 2 (target type) × 2 (initial target location) × 5 (interface condition) repeated measures ANOVA, which indicated that all main effects and interactions were statistically significant (p<.05) The *target type* × *initial target location* × *interface condition* interaction is illustrated in Figure 3.

The three-way interaction can be explained by noting the significant *initial target location* × *interface condition* interaction for ground targets, depicted in the upper portion of Figure 3, and the lack thereof for air targets (lower portion of Figure 3).

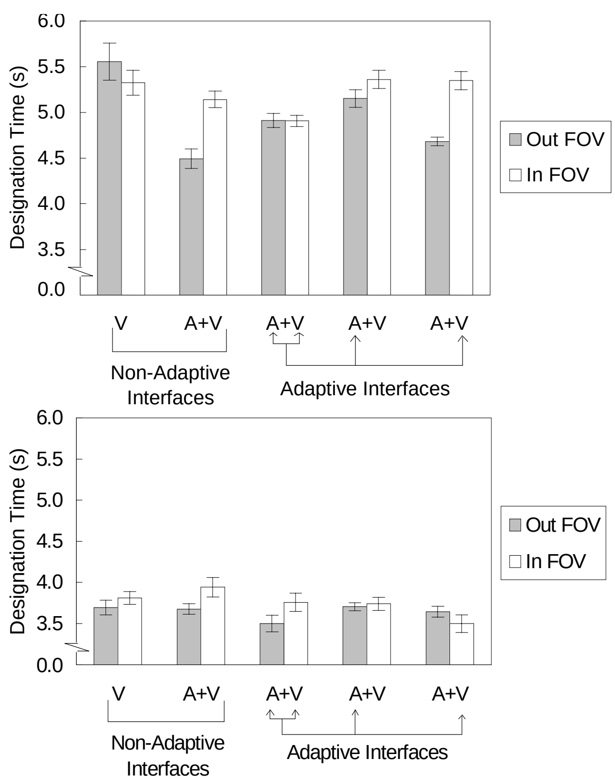

Figure 3. Mean designation times for ground (upper portion) and air (lower portion) targets as a function of initial target location and interface condition (A = Auditory; V = Visual; A+V = Auditory+Visual). As in the previous figure, non-adaptive and adaptive interface conditions appear on the left and right sides, respectively.

Two additional features that emerge from the data presented in Figure 3 are: 1) the significantly lower designation times associated with the air targets ($\overline{X}$ = 3.7 s) as compared with those for ground targets ($\overline{X}$ = 5.1 s); and 2) in the case of ground targets which initially were located outside of the operator's field of view, the average designation times of all combinations of multisensory interfaces was 825 ms faster than that for the visual interface condition.

Subjective Workload

Mean overall workload ratings on the NASA-TLX are presented for the seven interface conditions in Figure 4. It can be seen in the figure that ratings for the *Non-Cueing* and *Auditory* cueing conditions fell within the upper half of the workload scale, and were approximately 50% greater than those for the remaining interfaces, which fell within the lower half of the scale. A repeated measures ANOVA confirmed that there were statistically significant differences in the workload associated with the several interfaces, F(3,30) = 12.80, p < .05. Post-hoc tests indicated that the overall workload associated with both the *Non-Cueing* and *Auditory* interfaces was greater than that for each of the other interfaces. The workload ratings for both the Non-Cueing and Auditory conditions did not differ significantly from each other, and none of the remaining comparisons among the interface conditions reached significance (p > .05).

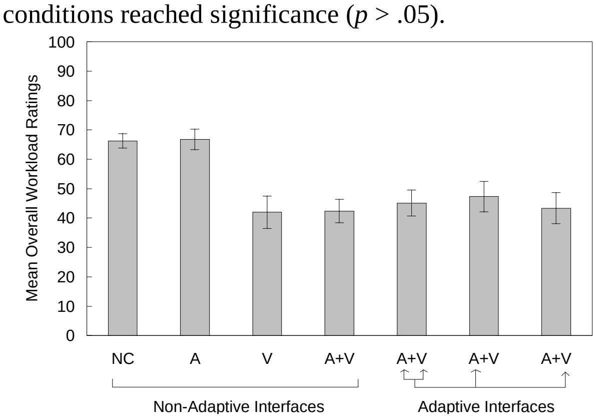

Figure 4. Mean overall workload ratings (NASA Task Load Index) for the seven interface conditions (NC = Non-Cueing; A = Auditory; V = Visual; A+V = Auditory+Visual).

Analysis of Head Motion Patterns

Head motion activity was examined by plotting head orientation in azimuth and elevation as a function of time for each experimental trial. Inspection of the resulting figures revealed two distinct patterns of head motion activity – one resembling a serial, non-terminating search of the field of regard, the other indicative of a series of brief ballistic head motions directed toward the targets. Examples of these two head motions patterns are illustrated in Figure 5. In general, the pattern displayed on the left side of the figure occurred in conjunction with the Non-Cueing condition, whereas the right portion of the figure characterized head motion patterns for all other experimental conditions.

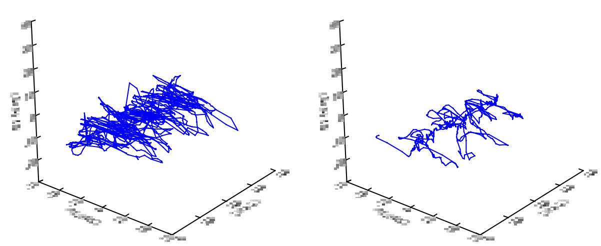

Figure 5. Examples of head motion patterns associated with the Non-Cueing (left side) and Visual+Auditory (right side) interface conditions.

The compelling nature of these data suggested a quantitative analysis based on the total angular displacement of the head. Due to methodological constraints, it was not possible to analyze these data in terms of *target type* and *initial target location*. Consequently, mean total angular displacements for the seven interface conditions were submitted to a one-way repeated measures ANOVA. Results of the analysis indicated a significant main effect, $F(2,20) = 187.03$, $p < .05$, which is illustrated in Figure 6.

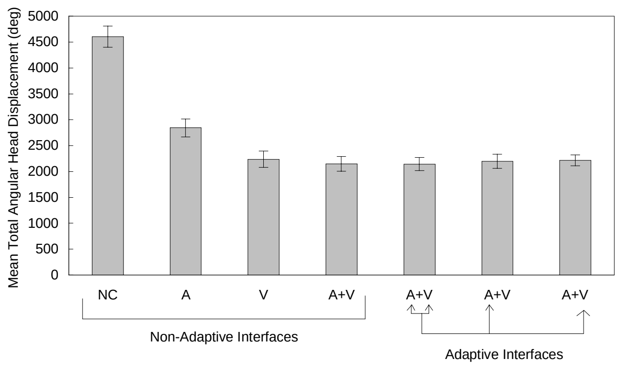

Figure 6. Mean total angular head displacement under all interface conditions.

DISCUSSION

While the multi-sensory interfaces were not found to be superior to the non-adaptive visual display in terms of target designation accuracy (Figure 2), total angular head motion (Figure 6), or perceived mental workload (Figure 4), they were associated with shorter designation times for ground targets that were initially outside of the pilot's field of view (Figure 3 upper panel). It is important to point out that these were the targets that were most difficult to detect: they contrasted poorly with the terrain, making it difficult to segregate them from the background. It should also be noted that the time advantage for the multi-sensory interfaces – approximately 825 ms – may be of considerable practical significance, given the overwhelming temporal demands that often confront tactical aviators.

It was surprising that performance efficiency under the non-adaptive auditory condition was found to be inferior to the non-adaptive visual condition. One plausible explanation for this result is the technical limitations of the spatial audio display (i.e., coarse resolution, non-individualized head-related transfer functions, time delay in the system, etc.), a line of reasoning that is consistent with the data provided by Bolia and his colleagues (in press).

A particularly striking outcome that results from the present investigation is that all cued (Visual, Auditory, and Auditory+Visual) interface conditions were associated with significantly lower ratings of overall workload than the Non-Cueing condition. This result is consistent with the analysis of the head motion data (Figures 5 and 6), which clearly demonstrated that the cued interface conditions produced more efficient search strategies (i.e., less head motion) than the non-cued display.

An additional observation was that the benefits provided by the multi-sensory interfaces did not come at the expense of flight performance (due to space limitations flight performance data were not presented in the results section). This outcome suggests that the multi-sensory displays did not incur an additional performance-resource debt (Weinstein & Wickens, 1992).

The results of the present investigation revealed no advantage for multi-sensory target information presented in an adaptive configuration, as opposed to a non-adaptive configuration. This may stem from the fact that the demands of this flight task were not sufficiently high to realize the benefits of the adaptive integration of visual and auditory information.

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